Optical Interferometry with Separated Spacecraft

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Section 386

March 11, 1996

Agenda

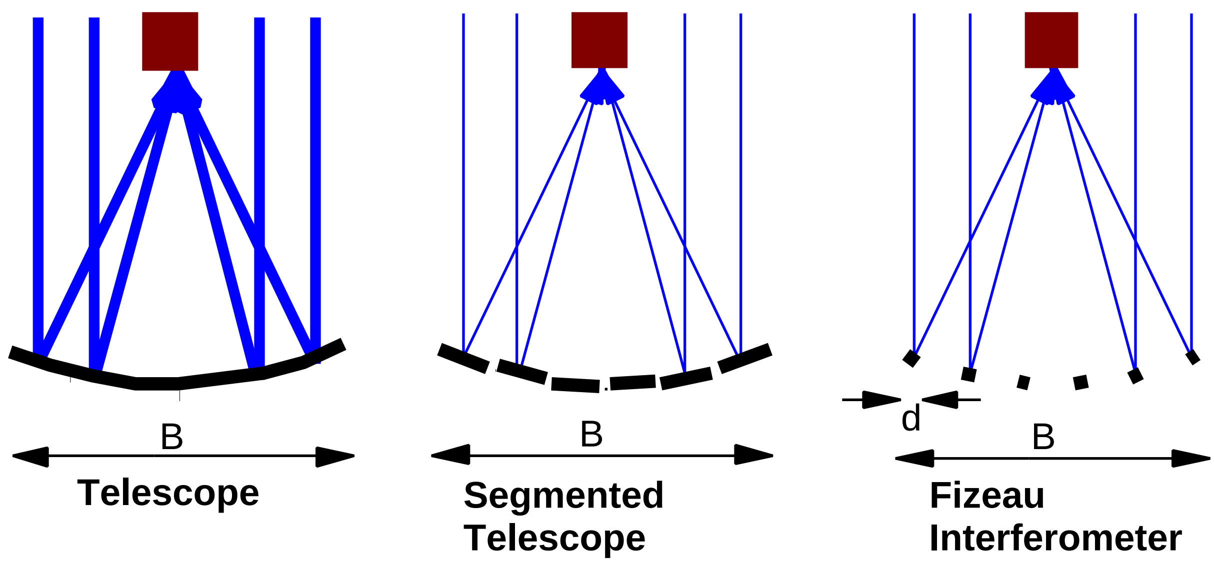
- Introduction to optical interferometry
- Separated-spacecraft interferometry
- The DS3 New Millennium Interferometer (NMI) concept
- Technology readiness for separated-spacecraft interferometry

Optical interferometry

- Interferometers coherently combine the light from several small, separated apertures to yield the angular resolution of a telescope as large as the separation
- Advantages of interferometry
  1. Higher angular resolution than is possible with a telescope
     - Telescope are limited to ~10 m (HST: 2.4 m; Keck: 10 m)
     - Interferometer baselines can be very large
  2. Much lower cost than an equivalent filled-aperture telescope
     - Interferometers decouple sensitivity (collecting area) from angular resolution (baseline)

All imaging is an interferometric process

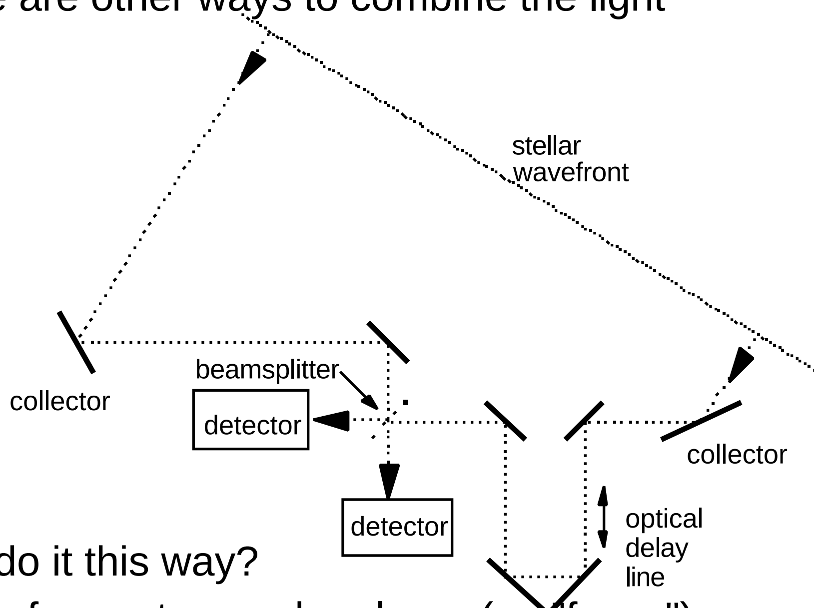
- A telescope is an interferometer which coherently combines the light from many small apertures which just happen to be adjacent to one another



	Telescope	Segmented Telescope	Fizeau Interferometer
Resolution:	λ/B	λ/B	λ/B
Sensitivity:	B^2	B^2	d^2

Michelson interferometry

- A Fizeau interferometer is essentially a dilute-aperture telescope
- There are other ways to combine the light

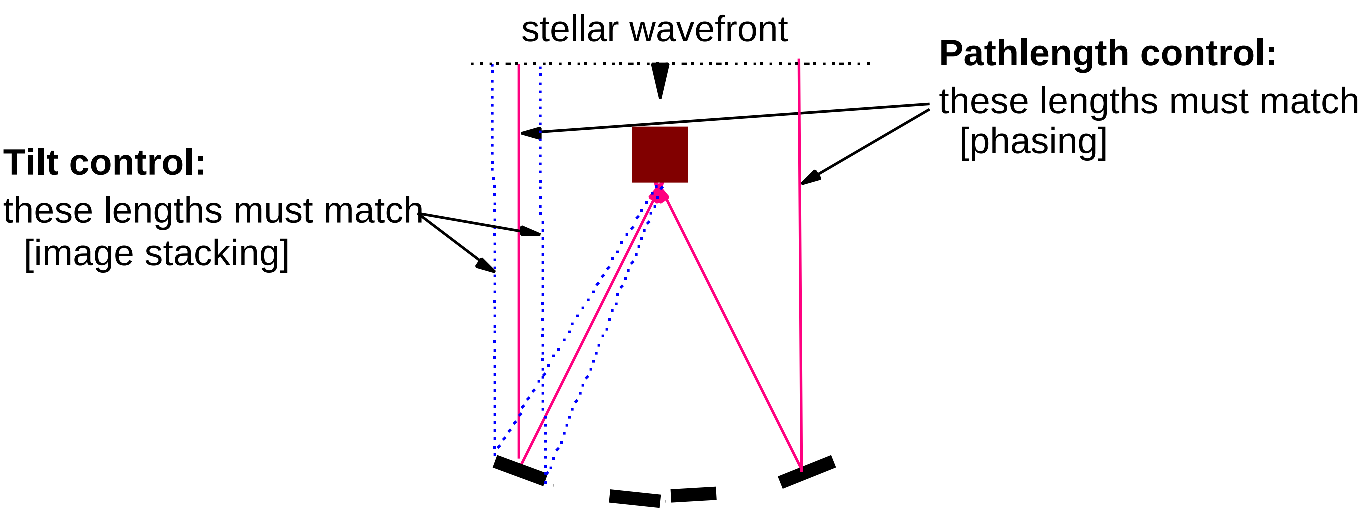


- Why do it this way?
  - Interferometer can be planar (no "focus")
  - Simpler detector requirements when array is very dilute
  - Allows for effective control of pathlength and wavefront tilt

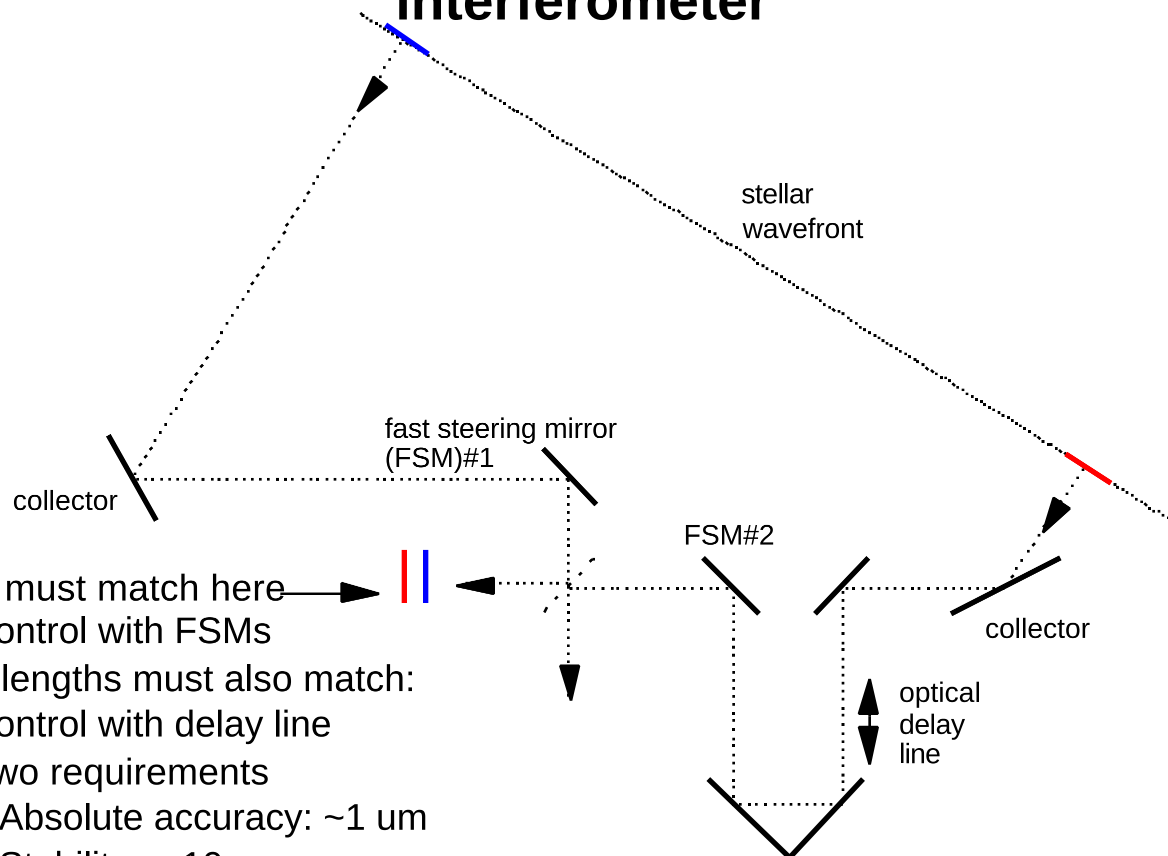
What are the challenges to doing interferometry?

- Maintain structural rigidity
  - Pathlength control
  - Tilt control
- Pointing of overall instrument - typically via an off-axis guide star

- Segmented telescope example:



Pathlength and tilt control with a Michelson interferometer

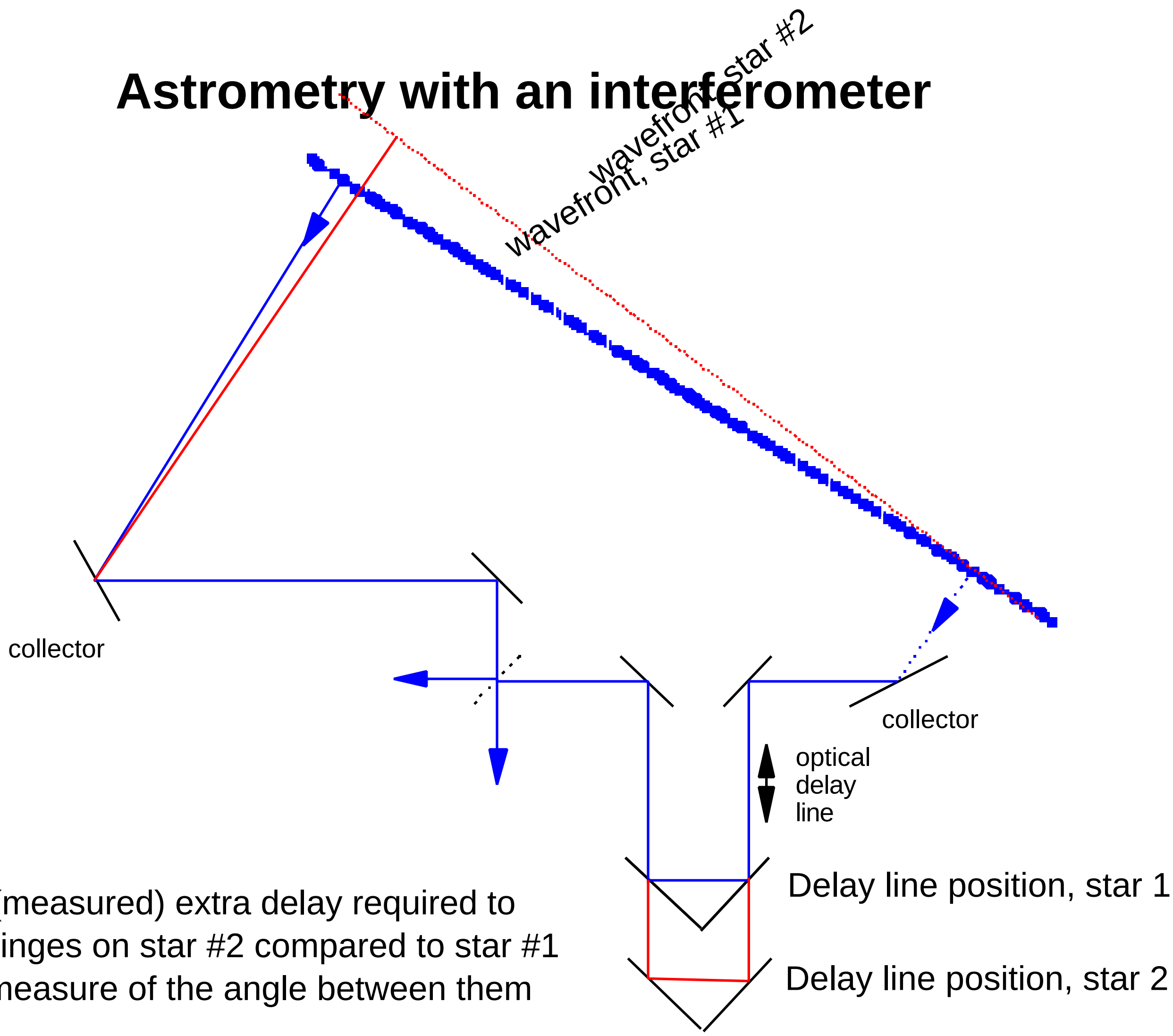


Tilts must match here
- Control with FSMs

Pathlengths must also match:
- Control with delay line
- Two requirements
  - Absolute accuracy: ~1 um
  - Stability: ~10 nm

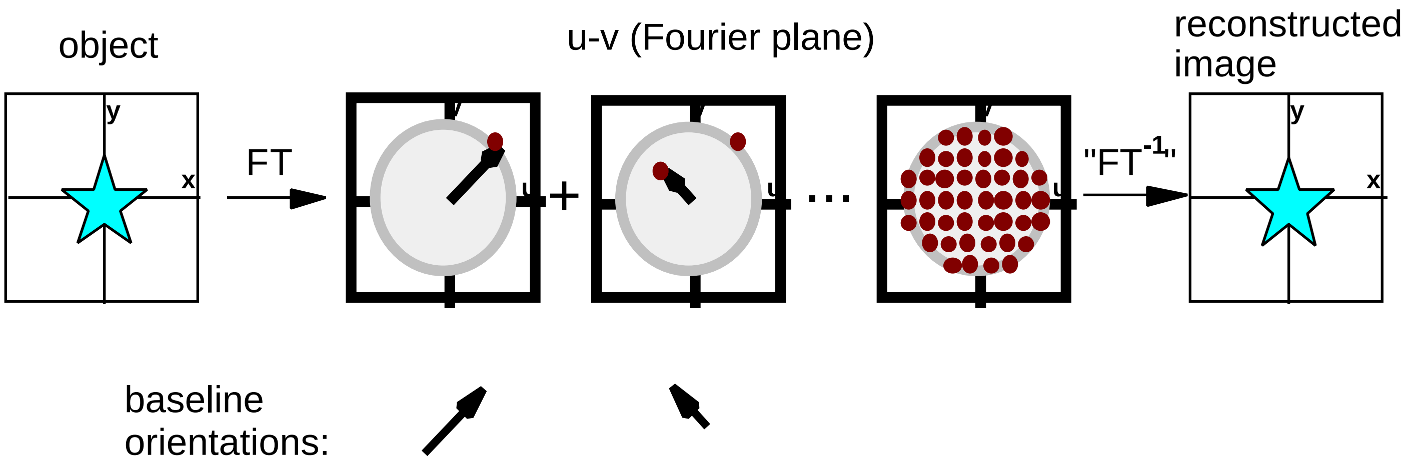
Note that tilt and pathlength control is done with small actuators inside the instrument

Astrometry with an interferometer



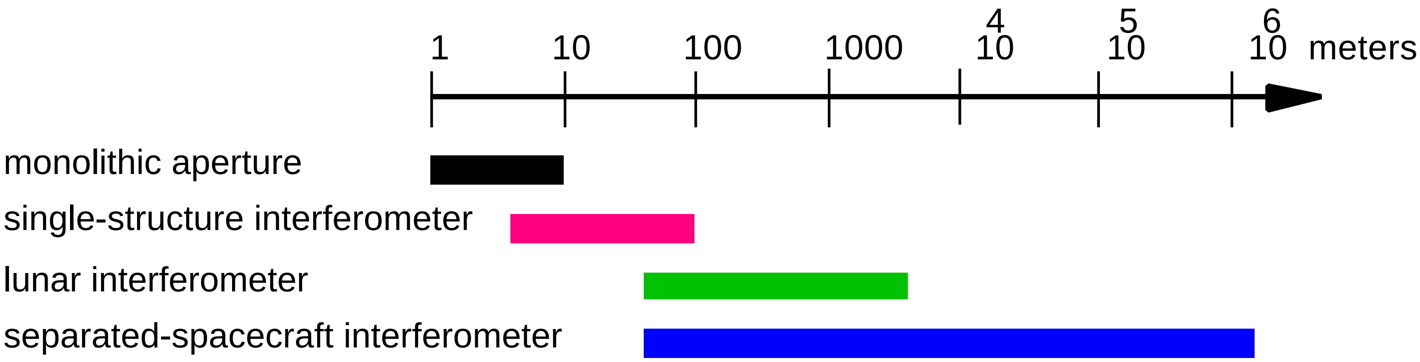
The (measured) extra delay required to get fringes on star #2 compared to star #1 is a measure of the angle between them

Imaging with a Michelson interferometer



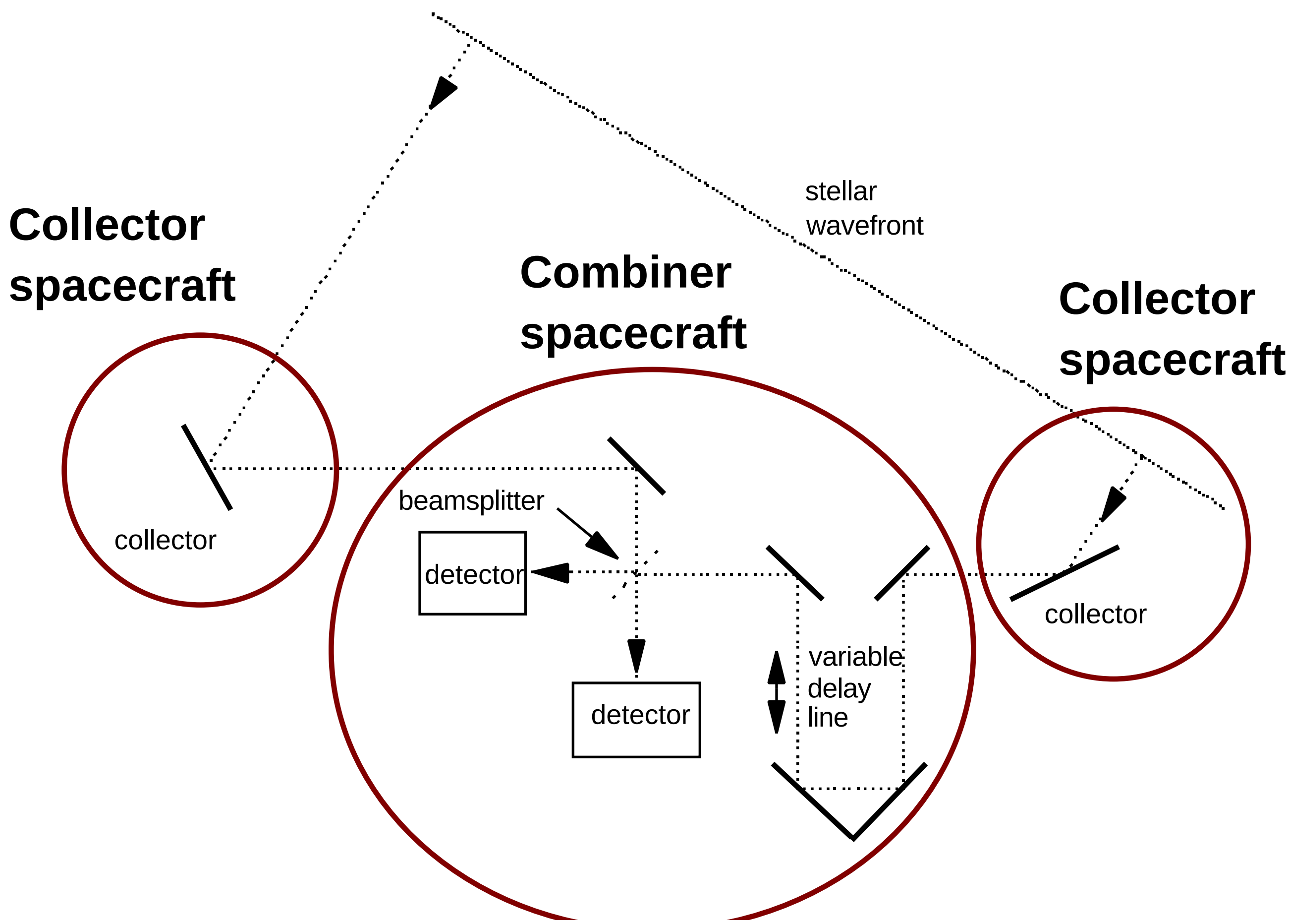
- The interferometer measures the Fourier transform of the object
- At each baseline orientation, you measure one (u,v) point
- With many baseline orientations, you fill in the (u,v) plane
- The inverse transform is done with algorithms originally developed for radio astronomy (CLEAN, MEM)

Achieving long baselines in space with separated-spacecraft interferometry



- Advantages of separated-spacecraft interferometry
  - Extremely long baselines are possible: allows measurements unachievable with other techniques
  - Easy to change baseline length and orientation
  - Allows for incremental array expansions and maintenance

How to build a separated-spacecraft interferometer



What are the challenges to doing separated-spacecraft interferometry?

- Maintain structural rigidity
  - Pathlength control
  - Tilt control
- Pointing of overall instrument

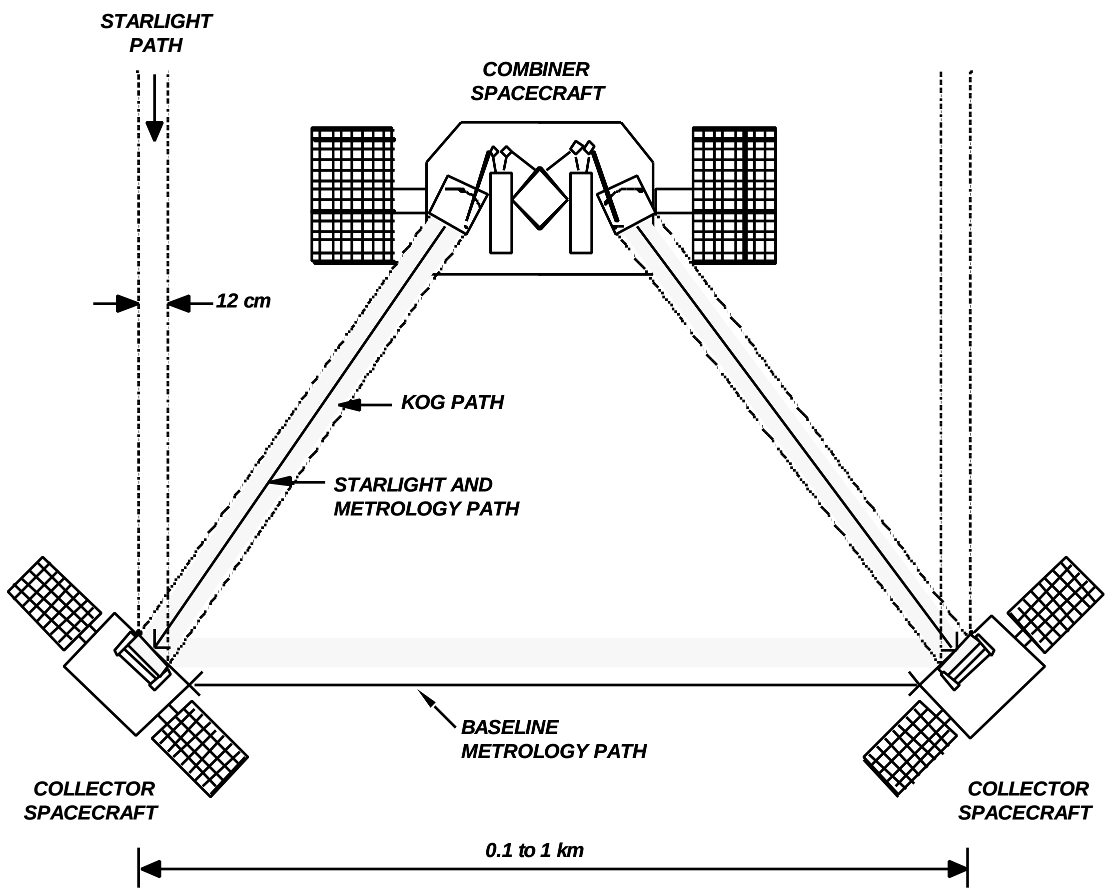
- I.e., same as for interferometry with single structures

- But
  - Now there's no structure
  - And you can't (easily) use off-axis guide stars for long baselines

New Millennium Interferometer (NMI) concept

- Proposed as third deep-space mission of the New Millennium Program
- Simplified separated-spacecraft interferometer that demonstrates key technologies, while still retaining science capabilities
- Major components
  - 3 spacecraft forming an interferometer constellation
    - 2 collector spacecraft, 100 m - 1 km apart, collect and relay light
    - 1 central combiner spacecraft, which combines and detects the light from the two collectors

New Millennium Interferometer



NMI objectives

- Demonstrate technology for future separated-spacecraft interferometers
  - ExNPS (Exploration of Neighboring Planetary Systems)
    - The near-term ExNPS roadmap calls for a 70+ m infrared interferometer
    - Separated spacecraft interferometry is one approach to implement the long baselines
  - EMM (Earth-Mapping Mission)
    - Long-term goal of ExNPS program
    - Separated-spacecraft interferometry is only way to achieve required baselines
- Demonstrate technology to enable other future missions: Earth-observing constellations and other instruments

Mission

- Nominal orbit: low-disturbance SIRTF-type Earth-escape orbit with maximum distance of 0.1 AU
- Nominal launch vehicle: Delta-Lite (Medlite family)
- Mission lifetime: 6 months
- Observation scenario
  - The plane of the three spacecraft will be approximately perpendicular to the sun vector to provide a uniform thermal environment, to simplify stray-light baffling, and to allow for fixed solar arrays
  - All stars are observable over 6-month mission

NMI science

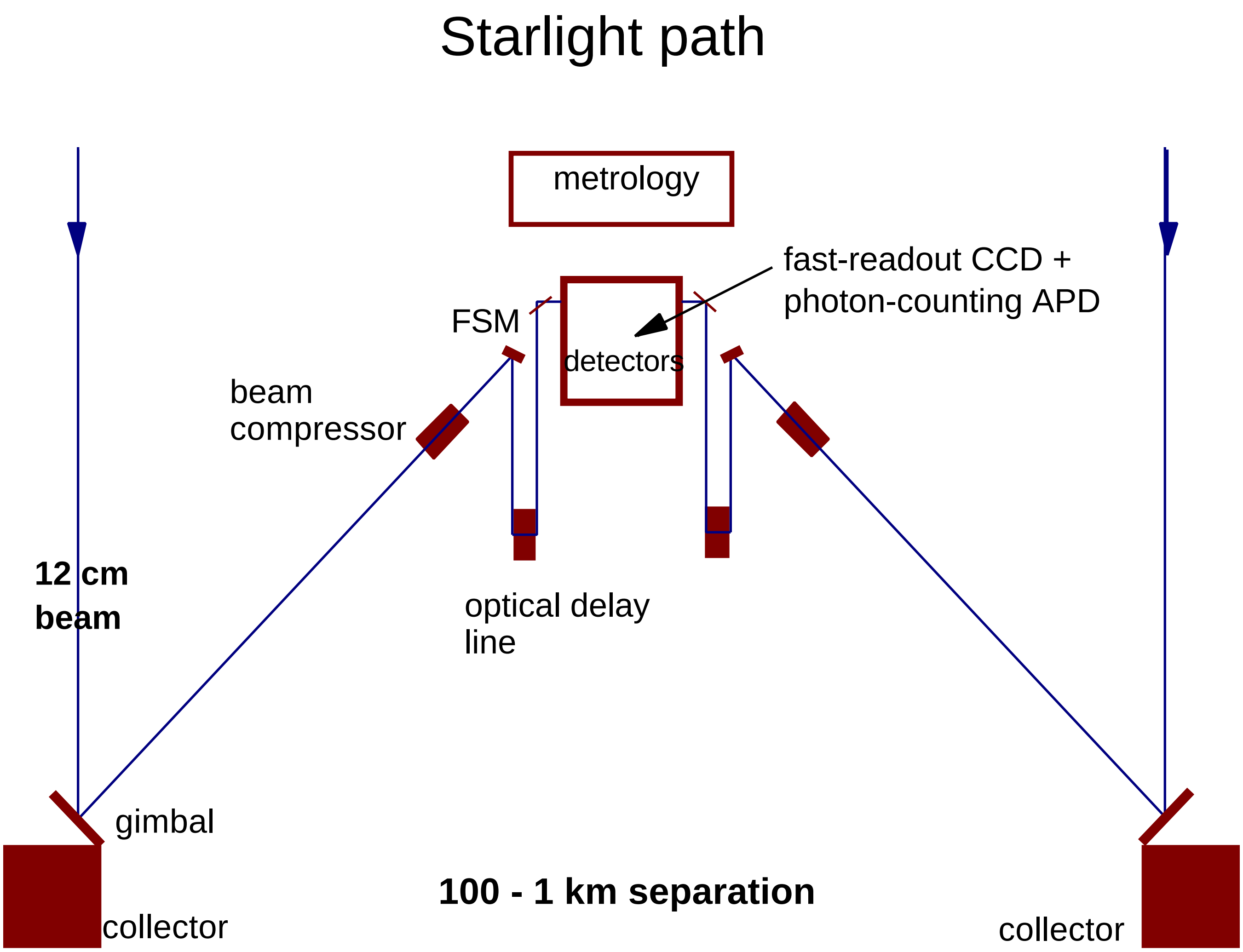
- NMI advantages over ground interferometers
  - Longer baselines: 100 m - 1 km
  - Higher sensitivity: to 14 mag
  - Better calibration due to lack of an atmosphere
- NMI limitations
  - Restriction to two apertures
- NMI science
  - Amplitude measurements on astrophysical objects
    - Diameters of faint stars
    - Binary-star orbits
    - Potential resolution of a bright quasar

Mission-enabling technologies

What	Why
1. Laser metrology 2. Active optical systems (delay lines, fast steering mirrors) 3. Formation flying controls	• Maintain "structural" rigidity (pathlength and tilt control)
4. Kilometric optical gyro	• Point the interferometer
5. Autonomous formation flying sensor	• Initialize the constellation
6. Starlight combination and detection	• Make the interferometric measurement
7. Multi-spacecraft interferometer systems integration	• Tie it all together

Starlight optics

- Collector spacecraft
  - Separation: 100 m to 1 km
  - Collect 12 cm beams of starlight
  - Gimbaled mirrors steer beams to combiner spacecraft
- Combiner spacecraft
  - Receives the 12-cm beams from the collectors
  - Compresses them to a more manageable size (3 cm)
  - Equalizes pathlengths using optical delay lines
  - Controls relative tilts using fast steering mirrors
  - Combines the beams and detects the interference signal


Starlight path
metrology
fast-readout CCD +
photon-counting APD
FSM
detectors
beam
compressor
12 cm
beam
optical delay
line
gimbal
100 - 1 km separation
collector
collector

Laser metrology

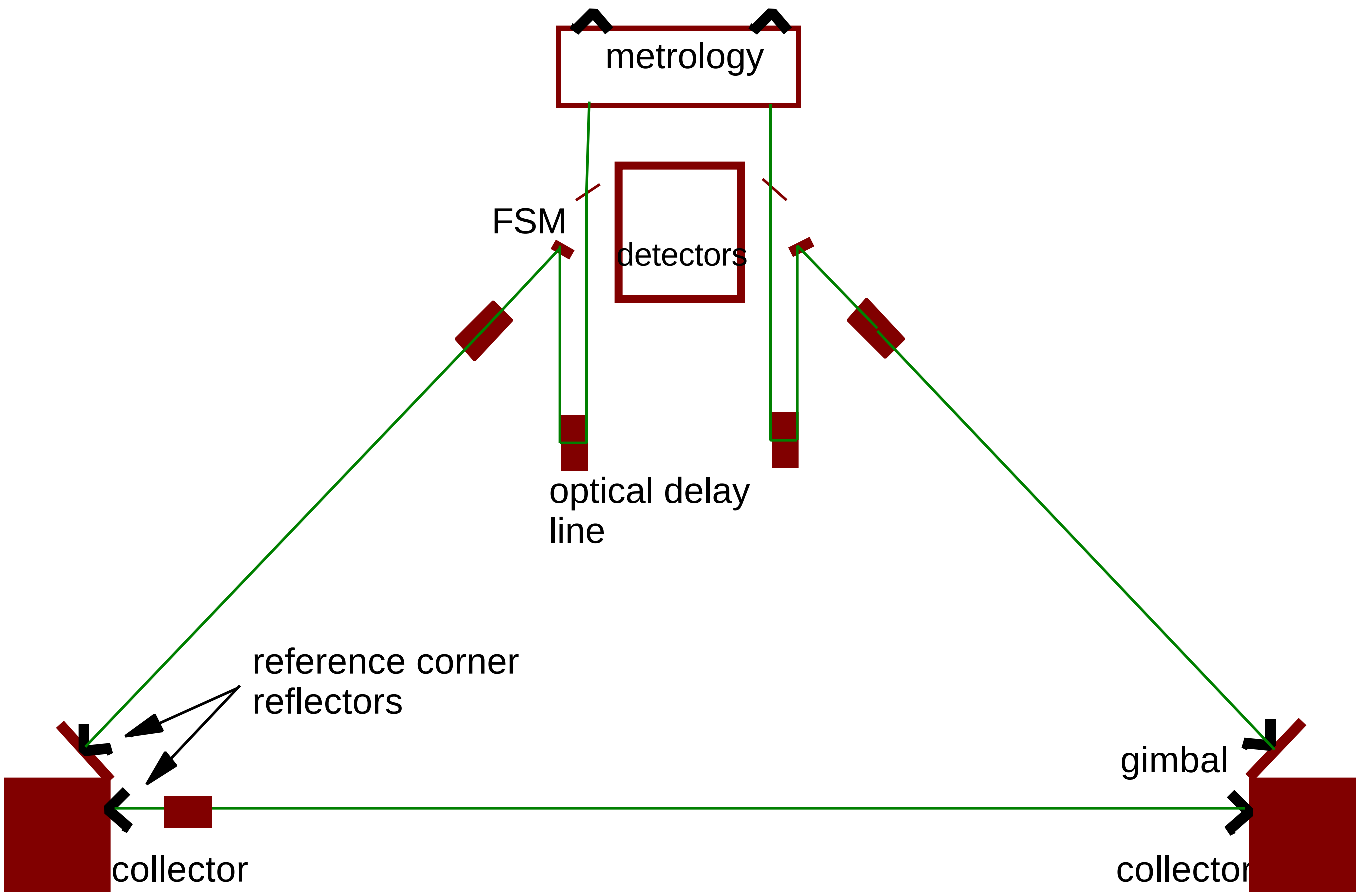
making the constellation appear as a rigid body

- For a separated-spacecraft interferometer, laser metrology beams replace the missing structural elements, measuring length changes along the paths
  - This data can be used to control the position of the spacecraft to the requisite level (10 nm)
  - Or, the data can be used to compensate for motion of the spacecraft by using the optical delay line

Laser metrology on NMI

- NMI uses 5 laser metrology beams
  - 2 measure the position of the optical delay lines to <10 nm
  - 3 measure the inter-spacecraft distances to <10 nm
- Proposed metrology implementation
  - Diode-pumped solid-state laser with frequency modulators to provide a heterodyne source
  - Fiber optics to distribute the signal

Metrology path



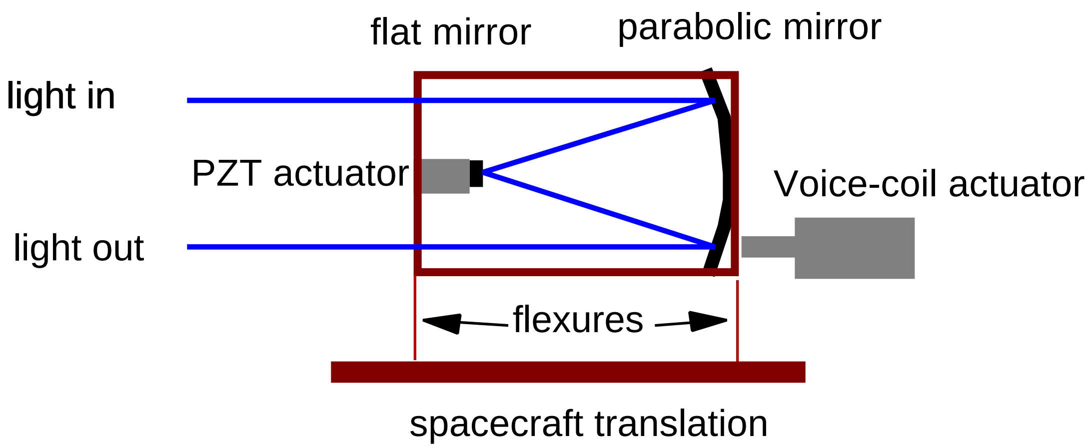
Active optics

- Optical delay lines: range of ~2 cm, control to <10 nm
  - Space-qualified version of design used on ground interferometer
- Fast steering mirrors (3 cm, 0.2" resolution)
  - For control of beam tilt
- Articulating gimbals (12 cm, 0.05" resolution)
  - 3-axis, for directing starlight and KOG signals

Formation flying

- The positions of the combiner spacecraft act as the coarse stage of the optical delay lines
  - The optical delay lines have a range of ~1 cm
  - The spacecraft with their propulsion systems need to maintain position to this tolerance
- Other propulsion requirements
  - Baseline orientation changes
  - Baseline length changes
  - Retarget between objects
- Candidate propulsion systems: Cold-gas or Teflon Pulsed-Plasma Thrusters (PPTs)

Optical path control:
Optical delay line + spacecraft control



actuator	resolution	range
PZT	1 nm	10 um
Voice coil	10 um	1 cm
Spacecraft	1 cm	---

Mission-enabling technologies

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1. Laser metrology 2. Active optical systems (delay lines, fast steering mirrors) 3. Formation flying controls	• Maintain "structural" rigidity (pathlength and tilt control)
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Kilometric Optical Gyro (KOG)
pointing the constellation

- Laser metrology with path length compensation by the delay lines make the constellation appear as a rigid body
- This rigid body must now be stabilized in rotation so as not to blur the image
- Problem:
  - Existing inertial references aren't nearly accuracy enough
  - Guide stars are not generally available
    - Too faint
    - Too resolved
- One solution: Kilometric Optical Gyro (KOG)

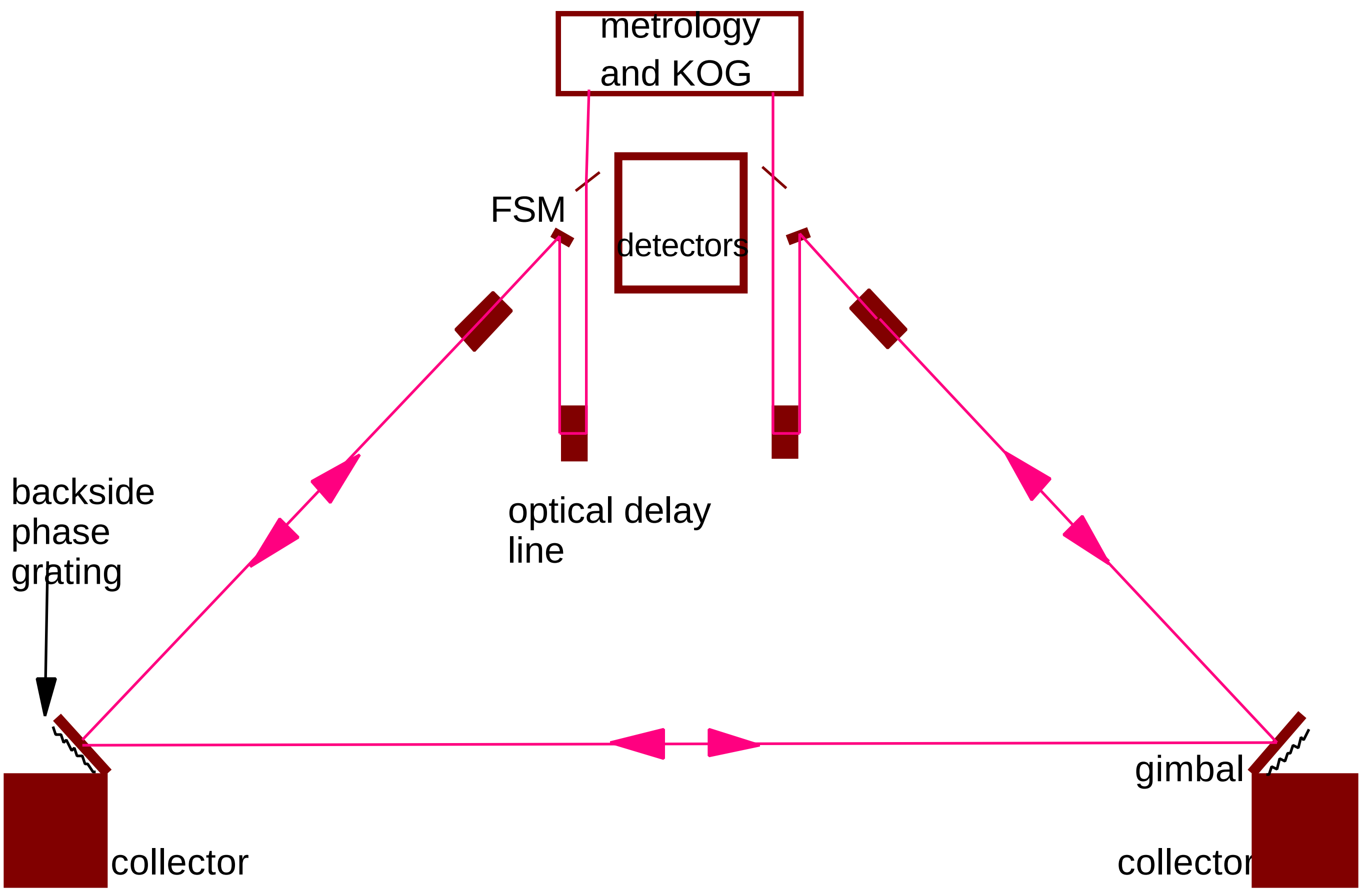
What's a KOG?

- It's a fiber-optic gyro, where the sensing coil is replaced by the set of three spacecraft
- More fundamentally, it uses a pair of counter-propagating laser beams among the three spacecraft
  - The phase shift between them is a measure of the rotation rate of the constellation
  - It provides a true inertial reference

KOG, continued

- KOG beam is coaxial with starlight
  - Injected in the beam combiner
  - Reflects off second-surface diffraction gratings on the collector mirrors
- Achievable coherence times of several seconds, depending on baseline
- KOG also has a surprising feature
  - Sensitivity of the KOG is proportional to enclosed area, or the square of the baseline
  - Pointing requirement is linear with baseline
  - KOG works better for longer baselines

Kilometric Optical Gyro (KOG) path



Autonomous Formation Flying Sensor

- Before the laser metrology system can work, the spacecraft need to be positioned to within the acquisition range of the metrology
- Trade study was conducted among a number of options
- Best alternative: Autonomous Formation Flying Sensor
  - Each spacecraft transmits and receives a GPS-like code to provide relative spacecraft ranges and angles
  - Target accuracy: 1 cm distance, 1 arcmin angle

Other technologies

- Starlight sensing and detection
  - Space-qualifiable versions of beam combiners, detectors, as used in ground-based interferometers
- Integration testbed
  - A ground testbed to integrate the starlight, metrology, and KOG systems with operational software to validate operation before flight

Technology readiness, I

- Interferometry technology
  - Ground-based experience
    - Palomar Testbed Interferometer
  - NASA Interferometry Technology Program (ITP)
    - Developing components, testbeds, and tools for the Space Interferometry Mission SIM and other interferometers

Technology readiness, II

- DS3-unique technology
  - Identified as part of this concept study
  - To be developed as part of the DS3 program
  - Technology includes
    - Formation flying: controls, sensor, and testbed
    - Kilometric optical gyro
    - Integration testbed

Conclusion

- Interferometer constellations are the only approach to providing ultra-high resolutions as required for future science missions
- Constellations are enabled by several key technologies
  - Laser metrology, active optics, KOG, formation flying
- DS3 will demonstrate these technologies, enabling these future science missions

Acknowledgments

- Ken Lau
- Jim McGuire
- Mike Shao
- Bob Laskin
- Gary Blackwood
- Jeff Yu
- Randy Bartman
- Bonny Schumaker
- Steve Lichten
- Larry Young